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Inferring energetic particle mean free paths from observations of anomalous cosmic rays in the outer heliosphere at solar maximum

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Abstract.

We find that the mean free pathlength is higher by a factor of 10 or more at solar minimum than at the last solar maximum in 1900-1991, consistent with previous findings. In 2000-2001, the mean free pathlength has declined by a factor of ~10, but is still larger by a factor of ~3.6 than its value of ~0.15 AU in 1990-1991. As solar maximum conditions become durably established in the outer heliosphere over the next few months, it may be possible to deduce the radial dependence of the mean free pathlength.

1 Introduction

Anomalous cosmic rays observed at Voyager 1 and 2 (V1 and V2) are pickup ions that have been accelerated at the solar wind termination shock (Fisk et al., 1974; Pesses et al., 1981) and propagated inward in the expanding solar wind. The propagation processes of convection and adiabatic deceleration are well determined because the solar wind speed has now been measured at essentially all heliolatitudes and at radial distances up to 60 AU at both solar maximum and solar minimum. However, the relative contribution of drifts and diffusion depends on the magnitude of the interplanetary mean free path, which has been more difficult to quantify as a function of particle rigidity and spatial position. At solar maximum, drift effects are likely suppressed and Stone and Cummings (1999) used a 1-dimensional spherically symmetric model of modulation to fit the V1, V2, and Pioneer 10 (P10) ACR O spectra during 1990/105-313 to find the mean free path, λ, in the rigidity range from ~1.4-4 GV. At 40 AU and 1.5 GV, they found that $\lambda \approx 0.15$ AU. This value is in good agreement with two theoretical models (Bieber and Matthaeus, 1997; Zank et al., 1998) for low latitudes. The models are distinguished by their differing radial and rigidity dependences. The Zank et al. (1998) fully-driven turbulence model ("NP1") has a rigidity dependence $\propto R^2$ and is independent of radius, whereas the Bieber and Matthaeus (1997) model is proportional to radius and the rigidity dependence transitions from R^2 at low rigidities to R^0 at higher rigidities. Both provided good fits to the Voyager and Pioneer ACR O energy spectra in 1990.

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Since 1990 to the present time, the conditions in the outer heliosphere have transitioned from solar maximum to solar minimum and back to solar maximum. The midpoint location of the two Voyager spacecraft has increased from ~40 AU to 72 AU (2001/78). In a previous study (Cummings and Stone, 1999) we found that λ increased by a factor of 10 or more from solar maximum to solar minimum. In that study we used only 4 periods at solar minimum up through the end of 1998. In this study we estimate λ for 12 solar minimum periods, providing complete coverage from the last solar maximum in 1990-1991 to mid-2000 and the onset of significant solar modulation in the outer heliosphere.

2 Observations and Analysis

Three techniques for inferring the mean free pathlength are employed: 1) a fit to ACR O spectra obtained for quiet days in 1991 using a spherically-symmetric model of modulation (Potgieter and Moraal, 1988; Stone and Cummings, 1999), appropriate for solar maximum conditions; 2) a calculation of ACR energy spectra of several ACR elements using a two-dimensional, full-drift model for the period 1998/1-1999/182; and 3) the force-field solar modulation solution (Gleeson and Axford, 1968) for the other time periods, which is one of the techniques we have used in past analyses of a similar kind (Cummings and Stone, 1997, 1999). We use the force-field solution for the period 1998/1-1999/182 as well to compare with the full-drift model.

2.0.1 Spherically-symmetric fit to 1991 spectra

For 1991, we find that the energy spectra of ACR O at V1 and V2 are very similar to those observed in 1990/105-313, which were subjects of a previous study of heliospheric char-

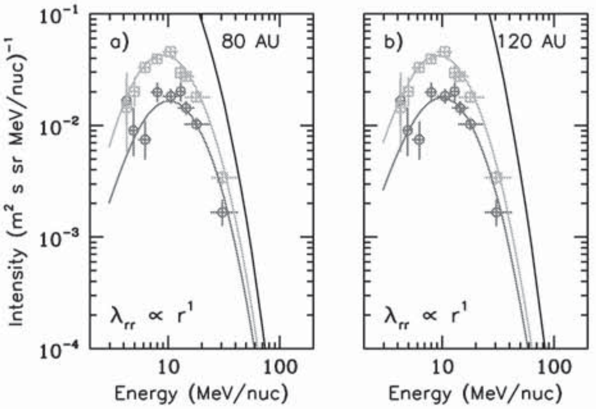

Fig. 1. a) Model fit to V2 (open circles) and V1 (open squares) ACR O energy spectra for 1991 for a shock location of 80 AU. The χ^2 of the fit is 15.3. b) Same as a) except for a shock location of 120 AU. The χ^2 is 13.7.

acterisitcs at solar maximum (Stone and Cummings, 1999). We thus carried out a fitting procedure very similar to the one used in that study. The energy spectra of ACR O and fits are shown in Figure 1. There were some non-quiet days in 1991 which were excluded. The periods of analysis were days 1-211 and 311-365 for V1 and days 1-147 and 294-365 for V2. The average locations were 45.1 AU and 31.5°N for V1 and 34.7 AU and 3.2°S for V2. We fixed the shock locations at 80 AU and 120 AU for the fits shown in Figure 1a and b, respectively, to get a range of possible mean free paths, since the fit was not sensitive to the shock location. We used a diffusion coefficient specified in Bieber et al. (1995) and Bieber and Matthaeus (1997), transformed for our purposes in Stone and Cummings (1999) (and labeled "KAP1" therein). It has the form:

$$\kappa = \frac{\kappa_0 \beta r \kappa_S R^2}{1 + (\kappa_S R)^2} \quad \mathrm{cm^2 s^{-1}} \quad (\mathrm{r} \gg 1 \text{ AU}) \tag{1}$$

where $\kappa_0 = 1.13 \times 10^{21}$, κ_S is a scaling factor, β is particle speed in units of c, and R is rigidity in GV. It has one free parameter, κ_S. The other free parameters in the fit were the shock strength and the particle intensity scaling factor.

The resulting rigidity dependences of the mean free path for the two fits are shown as the dotted lines in Figure 2. These are almost identical to the dependences found for the period 1990/105-313 and shown in Figure 2a of Stone and Cummings (1999).

2.0.2 2D, full-drift calculation for 1998/1-1999/182

For the period 1998/1-1999/182, a period of quiescent solar minimum conditions in the outer heliosphere, we have a study of ACR composition in preparation (Cummings et al., 2001) which uses energy spectra of 11 ACR elements and a sophisticated model of solar modulation (Steenberg, 2000) which adds the process of curvature and gradient drift in the large scale interplanetary magnetic field to the usual processes of diffusion, convection, and adiabatic deceleration.

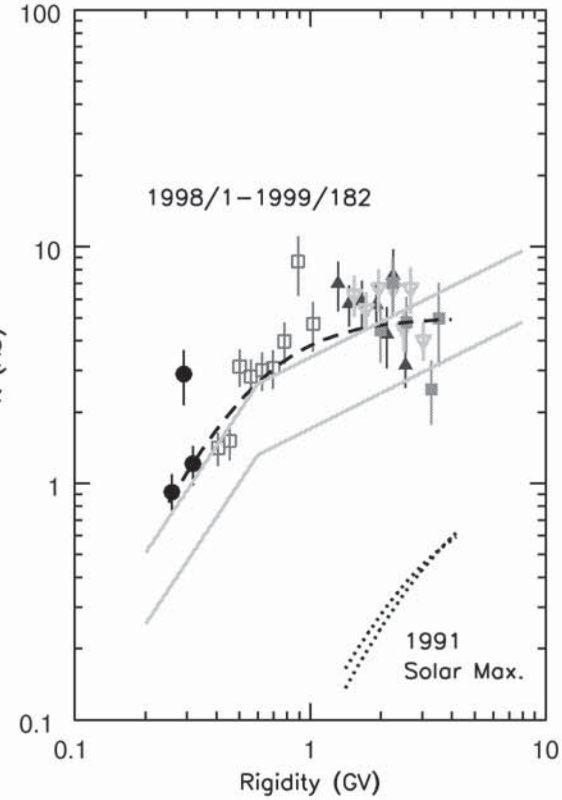

Fig. 2. Estimate of the mean free path in the outer heliosphere during the solar minimum period 1998/1-1999/182 and for a solar maximum period in 1991. The symbols are from the force-field technique based on the gradient of ACRs between V1 and V2 using different elements: H (solid circles), He (open squares), N (solid triangles), O (open inverted triangles), and Ne (solid squares). The dashed line is a fit to the points described in the text. The solid lines are from a two dimensional, full drift model fit (Cummings et al., 2001) to the V1 and V2 energy spectra. The upper solid line is λ_{rr} at the pole and the lower solid line is λ_{rr} at the helioequator. The dotted curves represent the allowable range from fits to the ACR O energy spectra in the outer heliosphere in 1991, assuming λ is proportional to heliocentric radius.

The model also accounts for charge-stripping during the acceleration process, which is important at total energies above ~350 MeV. In this model there are two mean free paths, λ_{rr}, the radial mean free path, and a smaller $\lambda_{\Theta\Theta}$, the mean free path in the polar direction. In addition, each is allowed to vary with polar angle. The rigidity dependence of λ_{rr} which provided a reasonable approximation of the energy spectra is shown in Figure 2.

2.0.3 Force-field solution

Following the method described in Cummings and Stone (1997) and Cummings and Stone (1999), we use the following equation to estimate the interplanetary mean free path:

$$\lambda = 3 < r >< C > V/(c\beta A) \tag{2}$$

where $< r >$ is the average radial position of V1 and V2 and $< C >$ is the average Compton-Getting factor for V1 and V2 energy spectra. C depends on the power-law index, γ, of the energy spectum and is given by $C = (2 - 2\gamma)/3$. $A = \ln(j_1/j_2)/\ln(r_1/r_2)$, which is determined from the V1 and V2 ACR energy spectra.

We applied this equation to energy spectra of 5 ACR elements acquired with the Voyager Cosmic Ray experiment on V1 and V2 for the period 1998/1-1999/182. We also applied it to yearly averaged ACR He and O energy spectra for the years 1992 through 1999 and for 52-day averaged ACR He and O energy spectra for 7 periods in 2000 and the first two 52-day periods in 2001. In each case we added 5% systematic uncertainties to the statistical uncertainties on the V1 and V2 intensity values and assumed 5% uncertainties in the value of C. Since we have concluded earlier that during the A>0 solar minimum the gradients are likely determined by conditions at high latitudes (Cummings and Stone, 1999), we used 750 $\pm$ 75 km s^{-1} for these periods (open triangles and open circle in Figure 4). For the other periods, we used 400 $\pm$ 40 km s^{-1} (solid circles in 2000-2001 in Figure 4).

During solar minimum some of the intensity gradient between V1 and V2 is due to a latitudinal gradient. From 1992 through mid-1996, we used V1, V2, and Pioneer 10 data to estimate the latitudinal gradient for ACR He and O in the $\sim$0.4-2 GV rigidity range. The average latitudinal gradient was 1.1%/deg. The effect of this correction to λ for the period, 1998/1-1999/182, is $\sim$40%, as shown in Figure 4 at 62-66 AU.

The results for 1998/1-1999/182 are shown as the symbols in Figure 2. The points appear to line up well with the polar value of λ_{rr} used by Cummings et al. (2001), consistent with the suggestion that the large mean free paths expected at high latitudes (Zank et al., 1998) during solar minimum are imprinted via particle drift processes onto the lower latitudes where the Voyager spacecraft are located.

The results for the other 17 periods are shown in Figure 3. The sudden change in character in period 2000.52.3 (third 52-day period of 2000) marks a transient increase in ACR He observed mostly at V2. By the next 52-day period, significant solar modulation effects have set in at both spacecraft (Cummings and Stone, 2001), and the mean free paths are reduced thereafter. The data indicate that typically λ increases rapidly from $\sim$0.4 to $\sim$1 GV but levels off above 1 GV.

3 Results

The dashed lines in Figure 2 and Figure 3 represent fits to the functional form:

$$\lambda = 3\kappa/(\beta c) = \frac{\lambda_0 (R/R_c)^2}{(1 + (R/R_c)^2} \tag{3}$$

where R_C is a roll-over rigidity. This form is like the KAP1 form of the diffusion coefficient (Equation 1) and is also the form we used sucessfully to fit V1 and V2 energy spectra in a spherically-symmetric model of modulation (Stone et al., 1996; Cummings and Stone, 1996). In Figure 4 we show the value of λ at 1.5 GV from the fits, as well as the values for the 1990-1991 solar maximum periods, as a function of the V1-V2 midpoint location. Except for the 1998/1-1999/182 period (62-66 AU) no latitudinal gradient correction has been applied. As a result, the mean free paths inferred during solar minimum are underestimated.

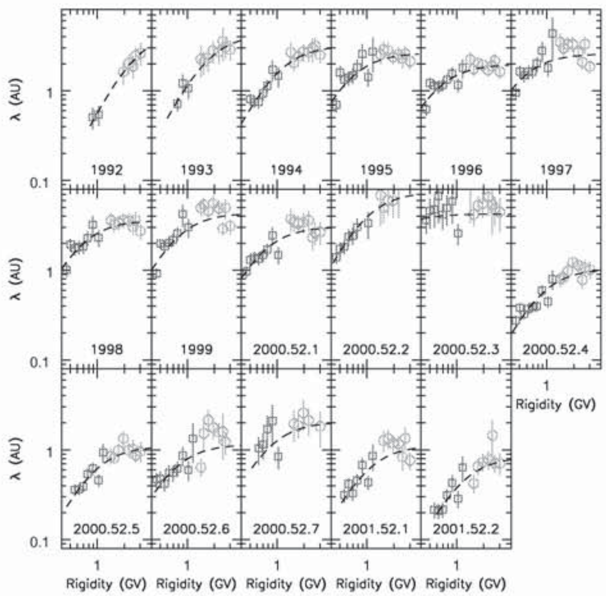

Fig. 3. Mean free path inferred in 17 time periods using the force-field technique described in the text. The open squares are for ACR He and the open circles are for ACR O. The actual mean free paths for 1992 through 2000 day 156 (2000.52.3) are likely somewhat larger than shown here because a correction for a small positive latitudinal gradient expected during solar minimum has not been made. The dashed lines are a fit to the data as described in the text. Points with uncertainties >50% of the value were excluded from the fits and are not shown.

The bottom panel of Figure 4 shows the tilt of the heliospheric current sheet and serves as a reference for the phase of the solar cycle. Large tilt values indicate solar maximum or near-solar maximum conditions and low values imply solar minimum conditions. λ appears to have a strong solar cycle dependence, being larger than at solar maximum by a factor of 10 or more. We attribute this to conditions at high latitude being imprinted to low latitudes via particle drifts. As solar modulation effects become significant at the Voyager spacecraft in 2000, λ begins to drop to lower values. For the last period in the study, 2001/53-104, λ =0.54 AU at 1.5 GV and 72 AU, a factor of $\sim$3.6 above the value inferred for 1990-1991 at 40 AU. This is larger than expected for either radial dependences of the theoretical diffusion coefficients which fit the 1990-1991 data so well, as shown in Figure 4. On the other hand, the points in 2000-2001 in Figure 4 appear to still be in transition and they may decrease further in the next few months. Once solar maximum is durably established in the outer heliosphere, it appears that it may be

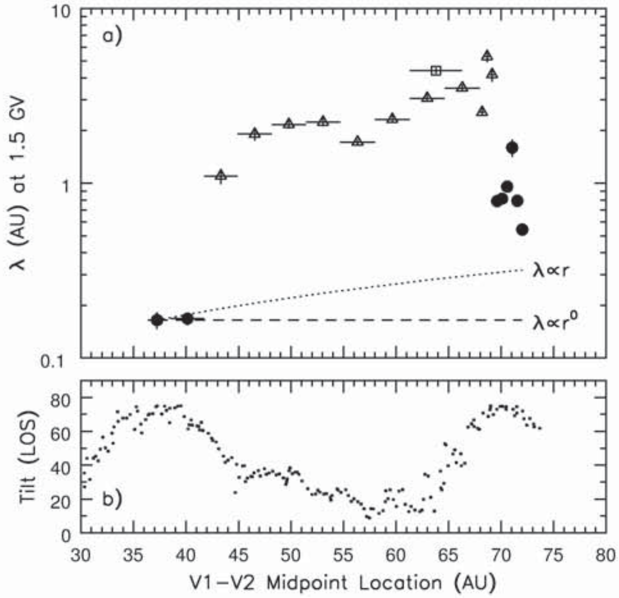

Fig. 4. a) Mean free path vs. V1-V2 midpoint location at 1.5 GV from the fits to the data shown in Figure 2 and Figure 3 (1992 and later). The value for 1991 is from the spherically-symmetric fit to V1 and V2 ACR O. The dotted and dashed lines refer to radial dependences of λ from Bieber and Matthaeus (1997) and (Zank et al., 1998), respectively. For the open symbols, a solar wind speed of 750 km s^{-1} was used and for the solid circles in 2000-2001, we used 400 km s^{-1}. The open triangles are somewhat underestimated since no correction for a positive latitudinal gradient was made. Such a correction was made for the 1998/1-1999/182 point (open square) which is ∼40% above the uncorrected 1998 and 1999 points. b) Tilt of the heliospheric current sheet (classic, line-of-sight method) from the Wilcox Solar Observatory shifted to the V1-V2 midpoint location using solar wind speeds from IMP-8 and ACE.

possible to determine the radial dependence of the mean free path.

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